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Energy Efficient and Reliable Smart Power Grids in Smart Cities using Edge Intelligence

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Abstract

Global energy consumption increases every year for the last centennial and it has only temporarily been slowed down in 2020 due to Covid-19 lockdowns. The goal of reducing energy consumption, without deteriorating the quality of life of citizens in a smart city seems nowadays to be both appealing and urgent. This will not only contribute in financial relief of citizens and countries, but it will also ease the global warming effect as well, because energy production requires fossil fuel which are CO2 producers.A micro grid is a self-sufficient energy system and the scope of a microgrid is to efficiently combine the production and consumption of electrical energy.Edge Intelligence (E.I.) is a process where data is aggregated and analyzed locally. Edge Intelligence enables machines to make decisions on the locally collected data, instead of sending it to a centralized cloud or on-prem server. Theories and methods of Fuzzy Cognitive Maps (FCM) can be used on Edge Intelligence. Simulations are performed with encouraging results in obtaining energy savings of a micro grid environment are presented.

1. Introduction

Energy efficiency is the use of less energy in a building to perform the same operation as buildings that consume energy inefficiently. Efficient energy consumption in buildings is one of the most affordable ways to lessen the detrimental effects of climate change and health-related problems. Energy-efficient homes and buildings use less energy to heat, cool, and run appliances and electronics. Similarly, energy efficient business uses less energy to provide services and products while energy-efficient manufacturing facilities use less energy to produce goods. Energy-efficient is a major component in developing nearly Zero-energy Buildings (nZEB). Energy efficiency is one of the easiest and most cost-effective ways to combat climate change, reduce energy costs for consumers, and improve the competitiveness of any business. Energy efficiency is also a vital component in achieving net-zero emissions of carbon dioxide through decarbonization.

A micro grid is a self-sufficient energy system that serves a discrete geographic footprint, such as a college campus, hospital complex, business center or neighborhood.

In this paper a micro grid consisted of residences, a school, a clinic, a generator and a solar farm, is studied in the direction of energy saving and reducing big data transfer to the power grid control center. The technique of Edge Intelligence in combination with Fuzzy Cognitive Maps (FCM)is

used. Using this technique will result in a)reduction of Power Consumption, b)optimum use of energy resources and c)less data transferred to the control center.

2. Background Related Information

Until now the power distribution grid was one way oriented, less efficient and slow in reactions and energy surpluses were produced because of the fear of peak demand blackouts. Furthermore, a small accident like a fallen tree could cause extended blackouts.

A smart grid is an electricity supply network that uses digital communications technology to react to usage changes. With the rising numbers of households and energy usage, there is also a rising interest in monitoring data related to energy production, usage or storage to maximize the customer experience, often using cloud computing-based applications.

However, the cloud has certain limitations. For example, an electricity company and/or the government may not want data from systems controlling the supply of electricity to be processed in a data centre outside their country. Secondly, in order to track supply and demand in real-time, plus use the data to predict both of these in advance, a huge number of sensors need to ingest information. Processing this in the cloud would be inefficient as it imposes significant costs from data transport and increases the potential for latency in processing time. Edge computing poses an alternative, by bringing computing closer to users and the source of the data. Furthermore, edge intelligence is edge computing combined with artificial intelligence (AI).

As mentioned before, a smart microgrid is a self-sufficient energy system that serves a discrete geographic footprint, such as a college campus, hospital complex, business center or neighborhood. Micro grid introduction is currently increasing. The islanding capability of the micro grid allows it to supply power to its customers when a storm or other calamity causes an outage on the power grid. In order for the micro grid to operate properly, it also has to communicate with the central power grid and exchange data and power. Similarly to the smart grid, the smart micro grid needs edge intelligence to do calculations and make decisions locally.

3. Basics of Edge Intelligence

With the breakthrough of Artificial Intelligence (AI),we are witnessing a booming increase in AI-based applications and services. AI technology, e.g., machine learning (ML) and deep learning (DL), artificial neural networks (ANN) achieve state-of-the-art performance in various fields, ranging from natural language processing, facial recognition, building energy efficiency, traffic control, computer vision, medical diagnosis, and hazard detection. Our lifestyles and every day activities have been dramatically changed due to the benefits from the services provided by these intelligent applications and services.

However, existing intelligent applications are computation-intensive, which present strict requirements on resources, e.g., CPU, GPU, memory, and network, which makes it impossible to be available anytime and anywhere for end users. Although current end devices are increasingly powerful, it is still insufficient to support some DL and ML methods. For example, most voice assistants, (e.g., GOOGLE Siri and its competitor Google Microsoft's Cortana, ALEXA or ELSA Speak), are based on cloud computing and they would not function unless users upload their data to central cloud-based datacenter. However, there is giant volume of data which has been generated, over the years and today, and collected by billions of mobile users and Internet of Thing (IoT) devices distributed at the network edge. Uploading such volume of data to the cloud

consumes significant bandwidth resources, which would also result in unacceptable latency for users. On the other hand, users increasingly concern their privacy. The subfield of Edge Intelligence (E.I.) comes to provide some solutions.

Edge Intelligence (E.I.) is a term describing a process where data is analyzed and aggregated in a spot close to where it is gathered in a network. This new inter-discipline, Edge Intelligence or Edge AI, is rightly receiving a lot of buzz today. Edge Intelligence enables machines to make decisions on the locally collected data, instead of sending it to a centralized cloud or on-prem server. Thus, Edge Intelligence (E.I.) refers to a set of connected systems and devices for data collection, caching, processing, and analysis proximity to where data is captured based on artificial intelligence. Edge intelligence aims at enhancing data processing and protect the privacy and security of the data and users. Although recently emerged, spanning the period from 2010 to now, this field of research has shown explosive growth over the past five years. As of today, smart edge applications promise real-time insights by analyzing data at the edge itself. This heralds a new technology that is incredibly exciting: Leading AI, DL and ML technologies, the cloud and hardware developments come together. This new scientific field need some methods outside the box of AI and the Fuzzy Cognitive Maps (FCM) and especially the state space theories are useful.

4. State Fuzzy Cognitive Maps With AI

The use of FCMs for modeling complex systems has proven to be very promising[1]. Their origin goes back in the 80's and they were another approach in the way of describing the relationship between concepts and analyze them [2-5]. They have since evolved to describe and model systems from economy to environment [6-16]. As an evolution of the FCMs, State Fuzzy Cognitive Maps offer a more qualitative approach and are especially used in ambiguous and fuzzy systems [17-20].

The concepts of input, state and output describe the inputs, characteristics and outputs of the system respectively. The State FCM are described by new equations (Eqs. 1–4) which help achieve higher convergence speed and more accurate results.

$$x[k+1] = x[k] + \frac{\Delta x[k+1]}{\sum_{j=1, j\neq i}^{n} |w_{ij}|} \tag{1}$$

$$y[k+1] = y[k] + \frac{\Delta y[k+1]}{\sum_{j=1, j\neq i}^{n} |w_{ij}|} \tag{2}$$

$$\Delta x[k+1] = A\Delta x[k] + B\Delta u[k] \tag{3}$$

$$\Delta y[k] = C\Delta x[k] + D\Delta u[k] \tag{4}$$

Δx[k+1], Δx[k], Δy[k] and Δu[k] are column vectors which describe the variation of input, state and output concepts. The process of calculating the variation (Eqs. 3–4) and then the final values of the concepts (Eqs. 1–2) is terminated when the concepts meet the following conditions:

$$F_1 = \sqrt{\sum_{i=1}^{m} (c_i(k) - T_i)^2} \tag{5}$$

$$F_2 = \left| C_j^{n+1} - C_j^n \right| \leq \varepsilon \tag{6}$$

where T_i is the optimal value and ε is the optimal difference between the values of two concepts (C).

The state FCM approach is described in [21,22].

In order for the State FCM methodology to be applied correctly, the values of all the concepts, inputs and initial conditions, must be between 0 and 1, with 0 being the smallest and 1 the largest value of a concept. However, the real values of the concepts do not usually belong to the desired interval. For this reason, Eq. 7 is used to transform their values to the desired interval. This equation offers, on the one hand, the ability to change the slope of the curve depending on the limits of each variable and once inverted (Eq. 8) allows to gain back the real value of the concept thus having accurate and interpretable results.

$$f(x) = m + \frac{M - m}{1 + e^{-r(x - t_0)}} \tag{7}$$

where x Є R and f(R)=(m,M)

$$f(x) = m + \frac{M - m}{1 + e^{-r(x - t_0)}} \tag{8}$$

where x Є (m,M) and f^(-1) ((m,M))=R

– m: lowest limit of the sigmoid curve

– M: upper limit of the sigmoid curve

– r: the slope of the curve and

– to: the point of symmetry with the y-axis

In this method we add Non-Linear Hebbian Learning:

$$W_{ij}^{(k+1)} = sign(W_{ij})^k [\gamma |W_{ij}^k| + \eta A_i^k [A_j^k - sign(w_{ji}^k)] W_{ji}^k A_i^k \tag{9}$$

and the calculating procedure is described in the following figure.

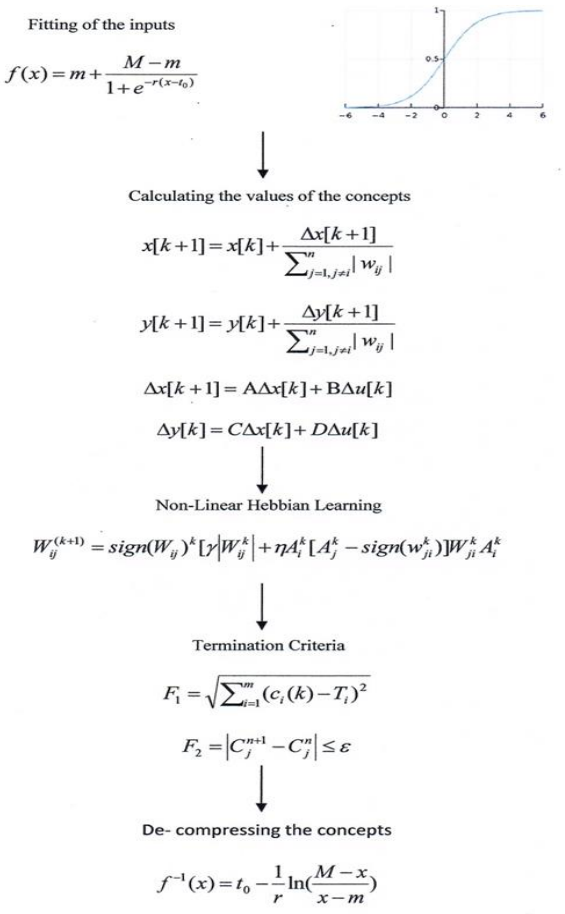

Figure 1: Calculating Procedure.

5. The Micro Grid

A micro grid is a self-sufficient energy system and the scope of a microgrid is to efficiently combine the production and consumption of electrical energy[23-24].

In our case, a micro grid consisted of residences, a school, a clinic, a generator and a solar farm is studied in the direction of energy saving and reducing big data transfer to the power grid control center. In order to efficiently model the microgrid which is presented in this paper, the authors studied previous attempts in modelling microgrids [25-30] and interviewed experts regarding the needs and potential of such a microgrid. After taking into consideration the opinions of the **experts**, the fuzzy cognitive map of the microgrid was formulated. In this case study, the inputs of the system will be the time of day, the day of the week, shading of the PV array (due to clouds, nearby trees etc), the environmental temperature and the solar radiation. The **states** of the micro grid are: Residences power consumption, school power consumption, clinic power consumption, PV power production, Generator production. Finally the **outputs** are: Total Power Production (micro grid) and Total Power Consumption.

6. Fuzzy Cognitive Maps construction

Given the experts' opinion the Concepts of the Fuzzy Cognitive Map for the micro grid system are as follows:

INPUTS

C1: time of day

C2: day of week

C3: Air temperature

C4: clouds

C5: solar radiation

STATES

C6: Residences power consumption

C7: school power consumption

C8: clinic power consumption

C9: PV power production

C10: Generator production

OUTPUTS

C11: Total Power Production(micro grid)

C12: Total Power Consumption

In the following table we see the weight matrix of the system.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1					0,4	0,3	0,45	0,2		
C2							- 0,15	- 0,28		
C3						- 0.3	-0.4	-0.4	0.05	
C4									0.62	
C5									-0.8	
C6										
C7										
C8										
C9										
C10										
C11									1	1
C12						0.6	0.1	0.4		

Table 1. Weight matrix.

The weights represent the causality between the concepts and are specified by experts who can estimate the right values based on their experience. The way the values of the concepts are calculated is described in [1].

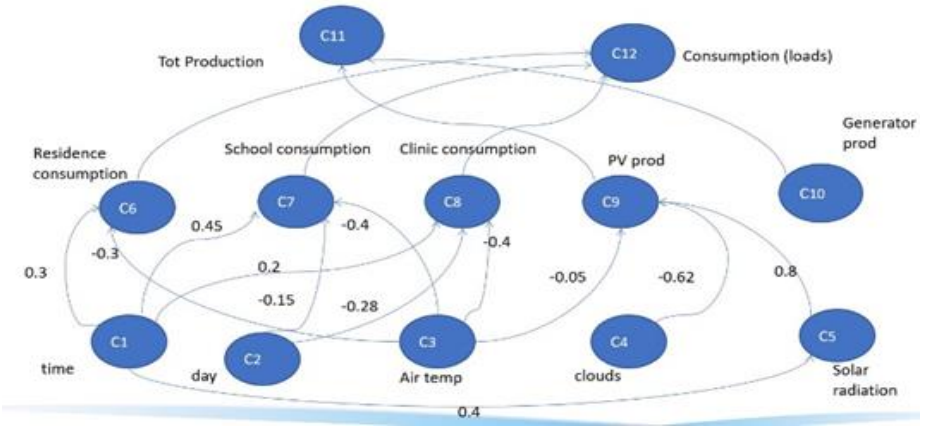

Figure 2: System's Fuzzy Cognitive Map.

7. Discussion of Results

The model of a smart micro grid was analyzed and processed using State FCMs with AI in the direction of reduction of Power consumption as well as optimum use of energy resources. Simulations are performed using only local data for the smart micro grid been considered. The simulations are done with theoretical values for the concepts of our smart micro grid system.

The results are encouraging and show for this analysis and simulation for a period of one month that the goals of energy reduction are achieved and show that energy saving up to 20% and more is achieved. This is in accordance with studies done in real situations, e.g., the University of Patras's buildings and elsewhere [22], [28].The simulations also demonstrated that the energy savings for the smart micro grid are obtained using only local data, thus utilizing Edge Intelligence. Another positive remark that can be made is that the proposed smart micro grid can be expanded very easily, without starting the modelling from zero.

8. Conclusions and Future research

With this type of research and undergoing investigation in this field, one can say that the technique of using state FCMs in combination with Edge Intelligence in Complex Dynamic Systems (CDS)such as Power Grids or Micro Grids, gives good results and helps us in understanding the behavior of CDS, which is very important in power management and therefore energy saving. The state FCM model used for analysis of smart cities concepts(smart grids, smart homes etc.) contains Artificial Intelligence and this helps us even more in achieving our main goal which is to optimize the operation of a smart city in terms of better management of energy flow using only local data.

In October 7 2022, Greece managed to operate its Power Grid for 5 hours, exclusively from Renewable Energy Sources(RES). As RES continue to grow and contribute more and more to the energy mix, the need for developing tools and methods that help us manage, control, self-repair, auto recover from faults in such CDSs like Power Grids, becomes urgent. By doing so, we will have more stable, reliable and efficient systems and research must turn to this direction.

Future research should concentrate in developing a larger smart micro grid system, develop the corresponding state FCM model and perform simulation studies with real data from small geographical regions of Western Greece.

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